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THE EFFECT OF STAGING ON THE RANGE OF UNDERWATER ROCKETS (U)

20 OCTOBER 1964

NOL

UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

NOLTR 64-173

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THE EFFECT OF STAGING ON THE RANGE OF UNDERWATER ROCKETS (U)

By

W. C. Ragsdale

ABSTRACT: A simple relation is derived for computing the range of a solid-propellant multi-stage underwater rocket. The rocket is assumed to consist of identical stages designed to give constant vehicle velocity and is assumed to travel horizontally. A comparison of the range of two- and three-stage rockets is given. The effect of staging and payload size on the range of a rocket powered anti-ship torpedo is considered as a specific example.

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Physical Chemistry Division
CHEMISTRY RESEARCH DEPARTMENT
U.S. NAVAL ORDNANCE LABORATORY
WHITE OAK, SILVER SPRING, MARYLAND

NOLTR 64-173 20 October 1964

The work reported here was carried out under Task RRRE-06019/212 1/F008-06-03, Underwater Rocket Performance. The factors influencing the performance of underwater rockets will be studied in this research program. This report describes an analytical study of the effect of staging on the range of underwater rockets.

R. E. ODENING
Captain, USN
Commander

Carl Boyers, for

ALBERT LIGHTBODY
By direction

LIST OF SYMBOLS

A	= total wetted surface area of vehicle, ft^2
C_D	= drag coefficient, dimensionless
D	= diameter of vehicle, ft
F	= drag force acting on vehicle, lbf
g_c	= conversion factor - 32.2 lbm-ft/lbf-sec^2
I_{sp}	= specific impulse of rocket motor, lbf-sec/lbm
L	= overall length of vehicle, ft
ΔL	= combined length of propellant grain and rocket nozzle for single-stage rockets, ft
$\Delta L'$	= length of propellant grain plus nozzle for multi-stage rockets, ft
n	= number of stages
N	= length of rocket nozzle, ft
P	= length of payload section, ft
R_1	= range of a single-stage rocket, ft
$(R_1)_{max}$	= maximum possible range for a single-stage rocket, ft
R_n	= range of a rocket with n stages, ft
T	= thrust of rocket motor, lbf
V	= vehicle velocity, ft/sec
W_p	= mass of propellant, lbm
α	= payload fraction, dimensionless
β	= nozzle fraction, dimensionless
θ	= burning time of rocket, sec
ρ	= density of water, lbm/ft^3
ρ_p	= propellant density, lbm/ft^3

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INTRODUCTION

The forces acting on an underwater rocket are the thrust of the rocket motor, the weight and drag of the vehicle and the buoyant force. Due to the relatively high density of water, the drag force is much larger for underwater rockets than for rockets operating in the atmosphere. As a result, underwater rockets usually travel at a terminal velocity, in contrast to atmospheric rockets which accelerate during burning and coast after burnout.

The total drag of slender bodies traveling underwater (such as torpedoes) consists almost entirely of skin friction drag and for this reason is directly proportional to the total wetted surface area (1). It is this fact that makes staging an attractive proposition for underwater rockets - under certain conditions. Underwater rockets are inherently inefficient, and, as a result, most of the vehicle volume is usually taken up by the propellant. As propellant is consumed, a progressively larger portion of the vehicle becomes an empty shell, contributing nothing to the thrust of the rocket but contributing significantly to the drag of the vehicle. By dividing the rocket into several stages, each having its own nozzle and propellant supply, the spent portions of the rocket may be discarded and the range or velocity of the vehicle increased accordingly.

The effect of one method of staging on the range of underwater rockets is considered in this report. None of the practical problems of staging have been considered.

ANALYSIS

In order to obtain simple relations for estimating the effect of various parameters and staging on the range of underwater rockets, the following assumptions are made:

1. Only solid propellant rockets are considered.
2. The rocket travels in a horizontal path. This implies that the effects of buoyancy and weight on the trajectory are neglected.
3. The rocket quickly reaches a constant terminal velocity where rocket thrust is equal to hydrodynamic drag.
4. In computing range, periods of rocket acceleration and deceleration are neglected. The range is taken as the product of the terminal velocity and the burning time.
5. The specific impulse is constant.
6. The drag force acting on the vehicle is assumed proportional to the total wetted surface area.

The assumption of constant vehicle velocity implies, in the case of a single-stage rocket, a constant chamber pressure if the rocket is traveling horizontally (assumption 2).

In order to achieve constant vehicle velocity with a multi-stage rocket it is necessary to vary thrust between stages. Following assumption (5), this can be accomplished by operating each stage at the same chamber pressure and using in each stage propellant having the same specific impulse* but different burning rate characteristics. Under these conditions, variation in thrust is due to variation in the mass discharge rate of the propellant from stage to stage.

Single Stage Rockets

The following additional assumptions are made regarding the single-stage underwater rocket:

1. The vehicle is assumed to be made up of a cylindrical payload section, a cylindrical propellant grain and a cylindrical nozzle section, as illustrated in Figure 1A.
2. The total wetted area is taken to be the lateral area of the cylindrical vehicle.

The thrust of the single stage rocket illustrated in Figure 1A is given by the following expression:

$$T = I_{sp}\frac{W_p}{\theta} = I_{sp}\frac{\pi}{4}D^2\left[\Delta L - N\right]\frac{\rho_p}{\theta} = I_{sp}\frac{\pi}{4}D^3\left[\frac{\Delta L}{D} - \frac{N}{D}\right]\frac{\rho_p}{\theta} \qquad (1)$$

where

T = thrust of rocket motor, lbf

I_{sp} = specific impulse of rocket motor, lbf-sec/lbm

W_p = mass of propellant, lbm

θ = total burning time, sec

D = diameter of the vehicle, ft

ΔL = combined length of propellant grain and rocket nozzle for single-stage rockets, ft

ρ_p = propellant density, lbm/ft^3

N = length of rocket nozzle, ft

---

*At a particular chamber pressure, ambient pressure, and nozzle expansion ratio.

The drag force acting on the vehicle is given by the following expression (assumption 6, p. 2):

$$F = AC_D\frac{\rho V^2}{2g_c} = \pi DLC_D\frac{\rho V^2}{2g_c} = \pi D[\Delta L + P]C_D\frac{\rho V^2}{2g_c} \tag{2}$$

$$= \pi D^2\left[\frac{\Delta L}{D} + \frac{P}{D}\right]C_D\frac{\rho V^2}{2g_c}$$

where

L = overall length of vehicle, ft

P = length of payload section, ft

F = drag force acting on vehicle, lbf

A = total wetted surface area of vehicle, ft^2

C_D = drag coefficient, dimensionless

ρ = density of water, lbm/ft^3

V = vehicle velocity, ft/sec

g_c = conversion factor - 32.2 lbm-ft/lbf-sec^2

Combining equations (1) and (2) and using assumptions 3 and 4 (p. 2) leads to the following approximate expression for the range, R_1, of a single-stage underwater rocket:

$$\frac{R_1}{D} = \left[\frac{g_c I_{sp}}{2C_D V}\right]\left[\frac{\rho_P}{\rho}\right]\left[\frac{1-\beta}{1+\alpha}\right] \tag{3}$$

where

$$\alpha = \frac{P/D}{L/D - P/D} = \frac{P/D}{\Delta L/D}$$

$$\beta = \frac{N/D}{L/D - P/D} = \frac{N/D}{\Delta L/D}$$

The maximum possible range of a single-stage rocket for given values of I_{sp}, ρ_P, C_D, D and V would occur when $\alpha = 0$ and $\beta = 0$. This corresponds to a hypothetical rocket made up entirely of propellant. Expressing the range in terms of the maximum possible value gives:

$$\frac{R_1}{(R_1)_{max}} = \frac{1-\beta}{1+\alpha} \tag{4}$$

where

$(R_1)_{max}$ = maximum possible range for a single-stage rocket $= D \left[\frac{g_c I_{sp}}{2C_D V}\right]\left[\frac{\rho_P}{\rho}\right]$,ft.

Due to their approximate nature, equations (3) and (4) are more useful as scaling rules to estimate the effect of α and β on range than as relations for determining the actual range of single-stage underwater rockets.

Multi-Stage Rockets

The following additional assumptions are made regarding multi-stage underwater rockets:

1. The vehicle is assumed to be made up of a cylindrical payload section and a number of identical stages, each consisting of a cylindrical propellant grain and a cylindrical nozzle section, as illustrated in Figure 1B.

2. The stages are assumed to be discarded as soon as they are completely burned.

The range of the multi-stage underwater rocket is determined by summing the increments of range obtained by burning each stage. Following the same procedure as for the single-stage rocket leads to the following expression:

$$\frac{Rn}{D} = \left[\frac{g_c I_{sp}}{2C_D V}\right]\left[\frac{\rho_P}{\rho}\right]\left\{\underbrace{\frac{\frac{\Delta L'}{D}-\frac{N}{D}}{n\frac{\Delta L'}{D}+\frac{P}{D}}}_{\text{1st Stage}} + \underbrace{\frac{\frac{\Delta L'}{D}-\frac{N}{D}}{(n-1)\frac{\Delta L'}{D}+\frac{P}{D}}}_{\text{2nd Stage}} + \ldots + \underbrace{\frac{\frac{\Delta L'}{D}-\frac{N}{D}}{\frac{\Delta L'}{D}+\frac{P}{D}}}_{\text{nth Stage}}\right\} \tag{5}$$

or,

$$\frac{R_n}{(R_1)_{max}} = (1-n\beta)\left\{\underbrace{\frac{1}{n(1+\alpha)}}_{\text{1st Stage}} + \underbrace{\frac{1}{n(1+\alpha)-1}}_{\text{2nd Stage}} + \ldots + \underbrace{\frac{1}{n(1+\alpha)-(n-1)}}_{\text{nth Stage}}\right\} \qquad (6)$$

where

$\Delta L'$ = length of propellant grain plus nozzle for multi-stage rockets, ft

n = number of stages

R_n = range of a rocket with n stages, ft

$$\alpha = \frac{P/D}{L/D-P/D} = \frac{P/D}{n\Delta L'/D}$$

$$\beta = \frac{N/D}{L/D-P/D} = \frac{N/D}{n\Delta L'/D}$$

Equations (4) and (6) may be used to compare the range of multi-stage rockets with the range of single stage rockets. It should be pointed out that such comparisons are restricted by the assumptions made in deriving equations (4) and (6). It is important to remember that only one method of staging has been considered, i.e., identical stages designed to give a constant vehicle velocity. Two additional assumptions will be made:

1. The single-stage and multi-stage rockets compared have the same value of α and β, i.e., the same values of D, L, N and P. Figure 1 illustrates this assumption.

2. The rockets compared have the same values of I_{sp}, C_D and ρ_P.

Combining equations (4) and (6) with these assumptions gives:

$$\frac{R_n}{R_1} = \frac{1-n\beta}{1-\beta}\left\{\frac{1}{n} + \frac{1}{n-\frac{1}{1+\alpha}} + \ldots + \frac{1}{n-\frac{n-1}{1+\alpha}}\right\} \qquad (7)$$

RESULTS AND DISCUSSION

Values of R_n/R_1 for two-stage and three-stage underwater rockets were calculated using equation (7) and are shown in Figure 2. These results show that the effect of staging on range becomes greater as either α or β are decreased. In other words, staging becomes more effective in increasing the range of an underwater rocket when the payload and nozzle sections make up a small portion of the vehicle. Thus, when α and β are zero the effects of staging are greatest. Using these limiting conditions the results show that the range of underwater rockets, under the assumptions made, could be increased by not more than about 50% if two stages were used instead of one and by not more than about 83% if three stages were used.

For large values of α and β the effects of staging are reduced and may actually be adverse. For example, when $\alpha = 0.5$ and $\beta = 0.12$ the range of a two-stage rocket is only 8 percent larger than a single stage vehicle and the range of a three-stage rocket is actually 1 percent smaller. This is due to the fact that as the number of stages is increased some propellant must be sacrificed in order to make room for the additional exhaust nozzles required. This effect finally offsets the beneficial drag reduction effect as the number of stages is increased.

The range of two-stage and three-stage rockets are compared in Figure 3. It can be seen that over a wide range of values of α and β the range of three-stage rockets is only slightly larger than that of two-stage rockets and is smaller than the range of two-stage rockets at large values of α and β. Hence, it appears that underwater rockets of three stages or more would be of little practical value.

To illustrate the various effects of staging on range discussed above, a specific rocket design will be considered.

A recently proposed design for a rocket powered anti-ship torpedo is shown in Figure 4 (2). Values of α and β calculated from the dimensions given in the figure are as follows:

$$\alpha = .538$$

$$\beta = .113$$

For these values of α and β, equation (7) indicates that the range of the torpedo could be increased about 8 percent if two stages were used but would not be increased if three stages were used. This illustrates the fact discussed previously that the effect of staging on range is either small or adverse at high values of α and β.

If the length of the payload of the proposed torpedo were decreased while maintaining the same overall length, the values of α and β would be decreased. The benefits of staging would become more pronounced at smaller values of α and β, as mentioned previously. The effect of decreased payload size on the range of the torpedo is illustrated in Figure 5.

The length of the proposed payload section is 86 inches. Figure 5 shows that if the payload length were cut in half (α reduced from .538 to .212; β reduced from .113 to .0885) and the same overall length were retained, the range of the single-stage torpedo would be increased 30 percent. The range would be increased an additional 22 percent if two stages were used instead of a single-stage, and 24 percent if three stages were used. A two-stage torpedo with the same overall length would have 60 percent more range than the proposed torpedo. In making these comparisons, the same exhaust nozzle length, N, has been assumed for all torpedoes.

In order to cut the length of the proposed payload section in half and retain the present total payload weight it would be necessary to repackage the components of the payload section so that the overall payload density would be .057 lb/in^3, about the same as that of TNT. The feasibility of doing this would probably depend on how much empty space could be eliminated from the guidance section. The use of a high density explosive would also help reduce the payload size.

In this report none of the practical problems of underwater rocket staging have been considered, such as stage ignition and separation. A highly idealized situation has been assumed in order to estimate the maximum possible effect of staging on the range of underwater rockets. The increases in range actually realized with a multi-stage rocket would probably be somewhat smaller than those estimated here.

Only one method of staging has been considered: equal-length stages designed to give a constant vehicle velocity. Many other methods of staging can be imagined, involving stages of different lengths designed to give different vehicle velocities. No attempt has been made to determine the optimum method of staging.

CONCLUSIONS

Under the assumptions made in this report, the following conclusions can be drawn concerning the effect of staging on the range of underwater rockets:

1. The range of underwater rockets can be increased by not more than 50 percent by using two stages instead of one and by not more than 83 percent by using three stages.

2. Staging is effective in increasing the range of underwater rockets only when the payload section and nozzle sections make up a small portion of the vehicle.

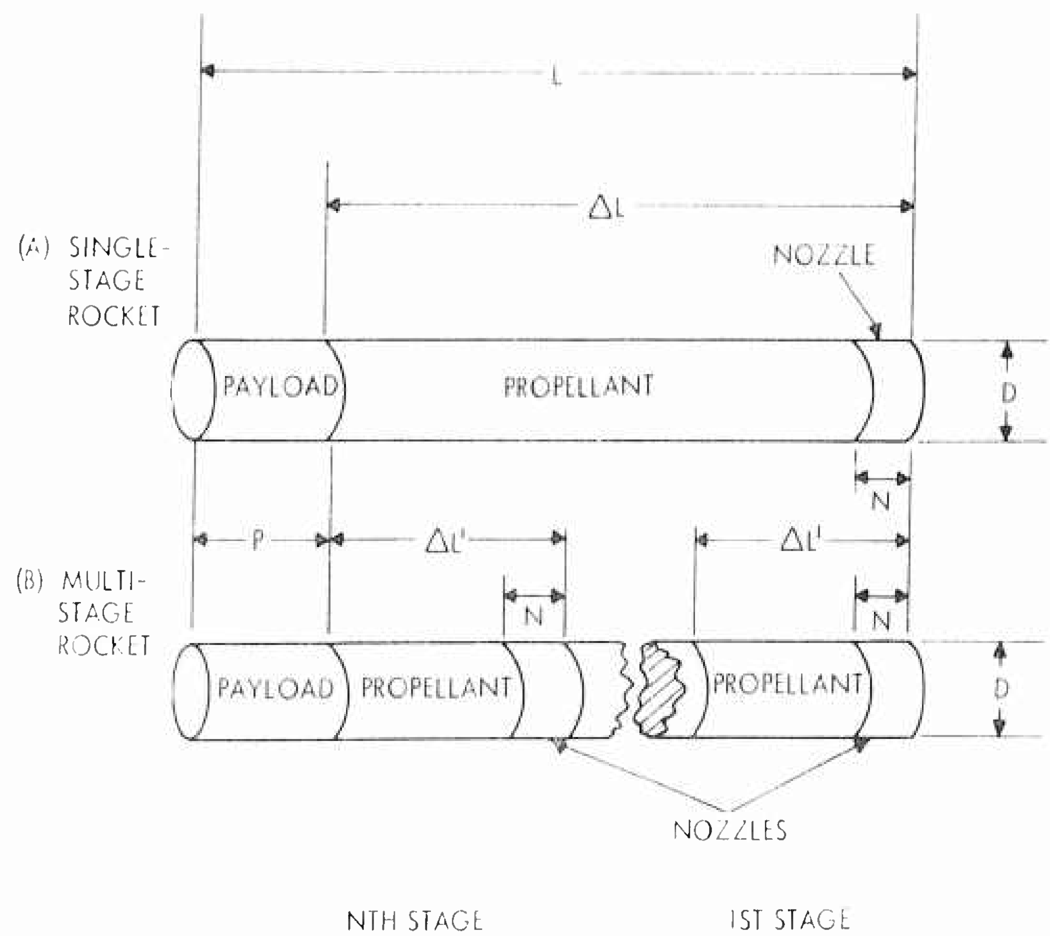
3. Staging has an adverse effect on range when the nozzle and payload sections make up a large portion of the vehicle.

4. Underwater rockets having more than two stages would be of little practical value.

REFERENCES

1. Hydroballistics Design Handbook - Chapter VI, NavOrd Rpt. No. 3533, March 1955. Conf.

2. "Anti-Ship Rocket Torpedoes - A Parametric Study", EPA-6, Allegany Ballistics Laboratory, Cumberland, Maryland, June 1962. Conf.



IN THE COMPARISONS MADE IN THIS REPORT
D, L, N AND P ARE THE SAME FOR THE ROCKETS
COMPARED

FIG 1 IDEALIZED UNDERWATER ROCKET CONFIGURATIONS

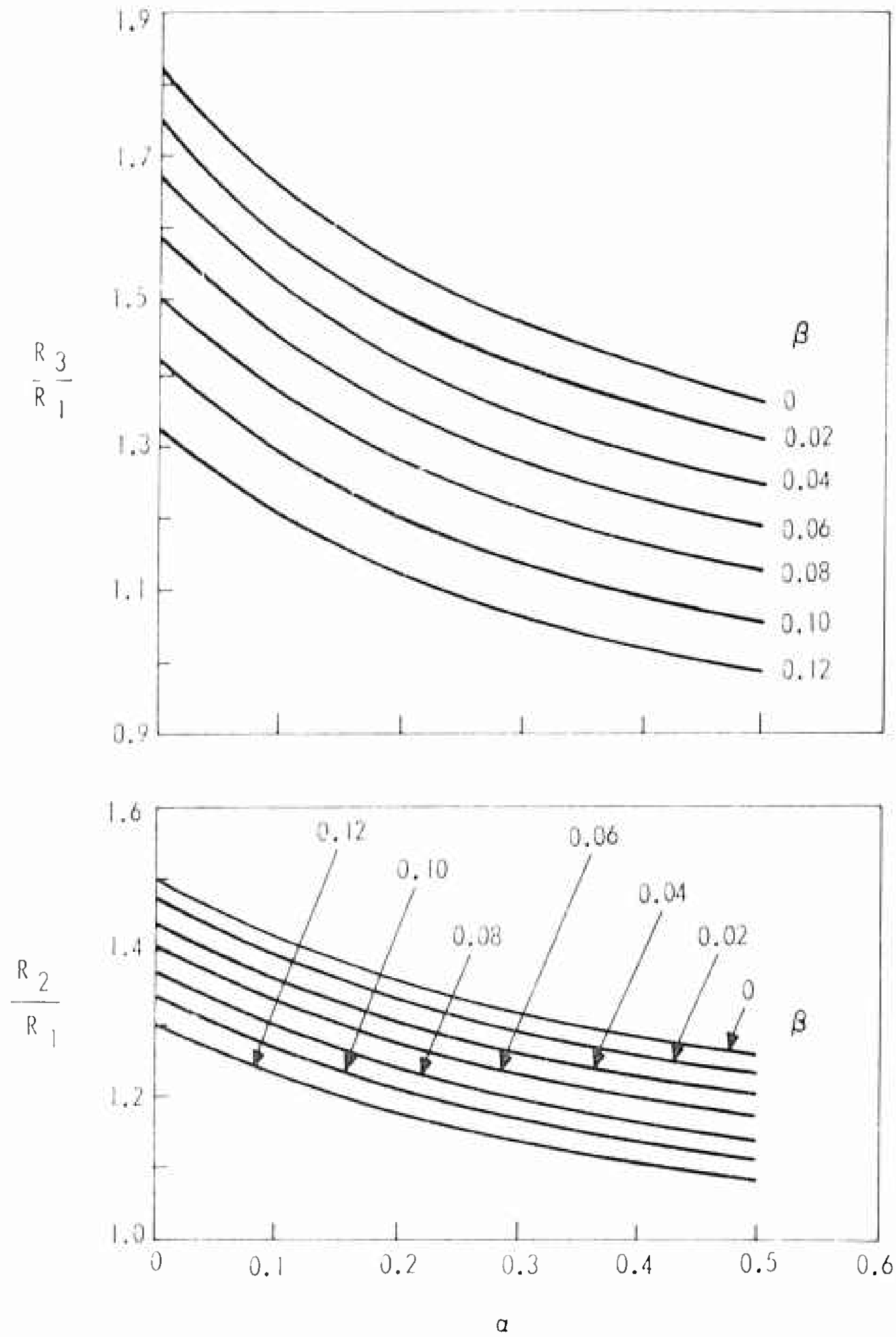


FIG 2 COMPARISON OF RANGE OF TWO-STAGE AND THREE-STAGE UNDERWATER ROCKETS WITH RANGE OF SIMILAR SINGLE-STAGE ROCKETS

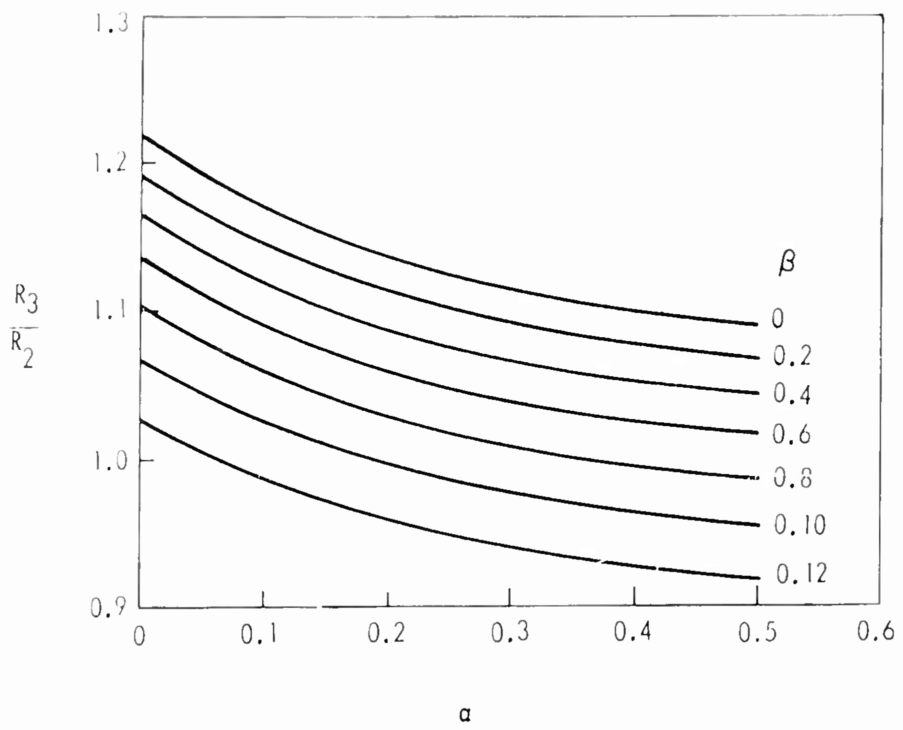
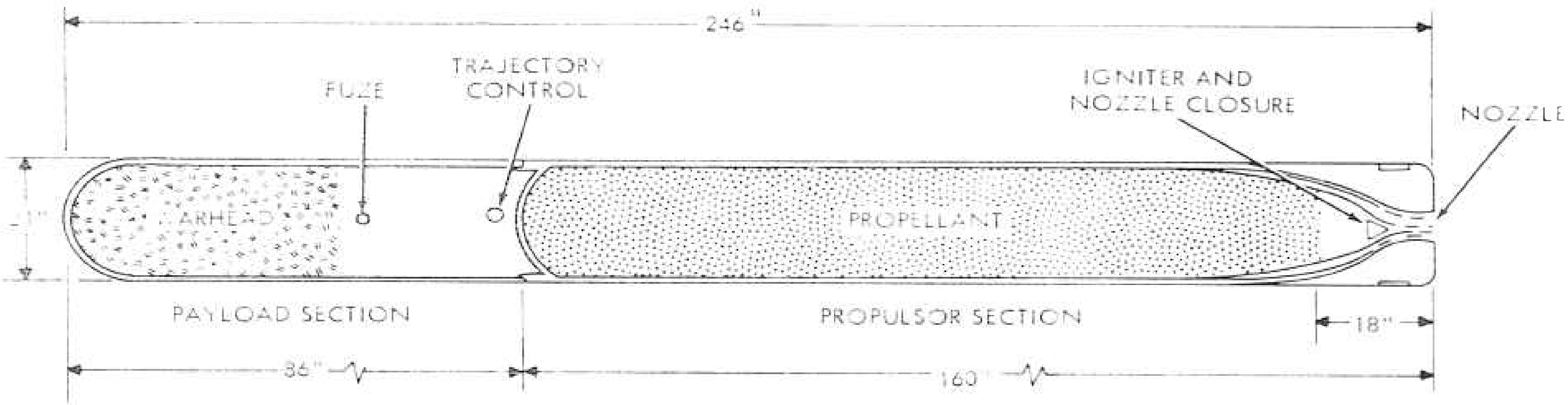


FIG 3 COMPARISON OF RANGE OF TWO-STAGE AND THREE-STAGE UNDERWATER ROCKETS



TYPICAL TORPEDO PARAMETERS

TOTAL WEIGHT (LBS)	4300
PROPELLANT WEIGHT (LBS)	3000
CHAMBER WEIGHT (LBS)	530
PAYLOAD SECTION WEIGHT (LBS)	770

Fig 4 PROPOSED SOLID PROPELLANT ROCKET TORPEDO CONFIGURATION

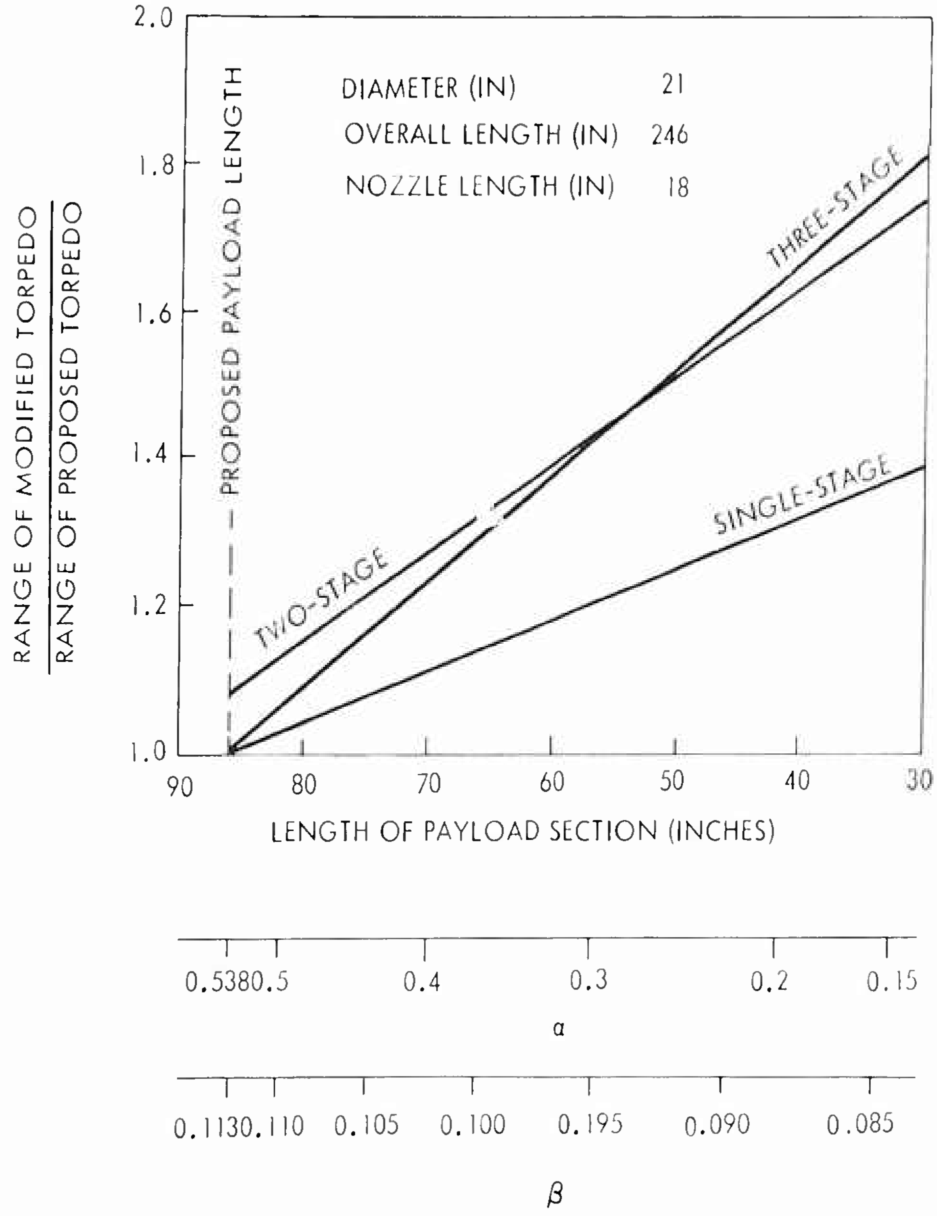


FIG 5 RANGE OF SINGLE AND MULTI-STAGE ROCKET TORPEDOES

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2. Rockets, Propellants
3. Rockets, Underwater

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Abstract card is unclassified.

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(NOL technical report 64-173)
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CONFIDENTIAL

A simple relation is derived for computing the range of a solid-propellant multi-stage underwater rocket. The rocket is assumed to consist of identical stages designed to give constant vehicle velocity and is assumed to travel horizontally. A comparison of the range of two- and three-stage rockets is given. The effect of staging and payload size on the range of a rocket powered anti-ship torpedo is considered as a specific example.

1. Propellants, Solid
2. Rockets, Propellants
3. Rockets, Underwater

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